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Smart Structural Performance Evaluation Using Digital Twin Simulation Technology: A Comprehensive Research

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ABSTRACT

This study examines the application of digital twin-based simulation for evaluating the structural performance of civil engineering structures. A digital twin creates a dynamic virtual model of a physical structure by integrating sensor data, BIM, finite element analysis, and predictive analytics. The study focuses on assessing stress, displacement, vibration, damage detection, maintenance planning, and service-life prediction under different loading and environmental conditions. The results indicate that digital twin technology improves monitoring accuracy, supports early damage identification, reduces maintenance uncertainty, and enhances infrastructure safety. Therefore, digital twins provide an intelligent and sustainable approach for life-cycle structural management.

Keywords: *Digital Twin, Structural Performance, Civil Engineering.*

I. INTRODUCTION

Digital Twin-Based Simulation and Structural Performance Evaluation of Civil Engineering Structures has emerged as a highly significant area of modern civil engineering because it integrates physical infrastructure with intelligent virtual modeling, real-time monitoring, and predictive analysis. In traditional structural engineering practices, the assessment of buildings, bridges, dams, tunnels, towers, and other civil engineering structures was mainly based on design assumptions, periodic inspection, manual testing, and simplified analytical models. Although these methods have contributed greatly to structural safety and serviceability, they often fail to capture the continuous and complex behaviour of structures under real environmental and loading conditions. Civil engineering structures are exposed to multiple actions throughout their service life, including dead loads, live loads, wind forces, seismic vibrations, temperature variations, moisture effects, corrosion, fatigue, settlement, material degradation, and accidental impacts. These factors gradually influence the strength, stiffness, durability, and overall performance of structures. In many cases, early signs of structural distress remain hidden until visible cracks, excessive deflection, vibration problems, or failure symptoms appear. This creates a need for advanced evaluation techniques that can continuously monitor structural health, predict possible damage, and support timely maintenance decisions. A digital twin provides an effective solution to this problem by creating a dynamic virtual representation of a physical structure. Unlike a static computer model, a digital twin is continuously updated through data collected from sensors, Internet of Things devices, drones, laser scanning, Building Information Modeling platforms, and structural health monitoring systems. It combines real-time field information with simulation techniques such as finite element analysis, computational modeling, machine learning, and data analytics. Through this integration, the digital twin can represent the actual condition of a structure more accurately than conventional models. It can simulate stress distribution, strain variation, displacement response, vibration behaviour, crack development, fatigue damage, load transfer mechanisms, and remaining service life. In civil engineering, this capability is highly valuable because infrastructure systems are becoming larger, more complex, and more vulnerable to aging, overloading, climate change, and natural disasters. The growing demand for smart cities, sustainable construction, resilient infrastructure, and cost-effective maintenance has further increased the importance of digital twin-based structural evaluation. By linking the real structure with its virtual counterpart, engineers can observe performance changes, compare expected and actual behaviour, identify abnormal responses, and make informed decisions regarding repair, strengthening, retrofitting, or replacement. Thus, digital twin technology is not only a modeling approach but also a decision-support system that improves the safety, reliability, and sustainability of civil engineering structures.

The application of digital twin-based simulation in structural performance evaluation offers a transformative approach for understanding how civil engineering structures behave throughout their complete life cycle. During the design stage, a digital twin can help engineers test different structural configurations, material choices, load combinations, and environmental scenarios before actual construction. During the construction stage, it can support quality control, construction progress monitoring, and error detection by comparing the planned model with the actual built condition. During the operation and maintenance stage, it becomes even more useful because it continuously receives data from the physical structure and updates its analytical model accordingly. For example, sensors installed on a bridge can measure vibration, strain, temperature, displacement, and traffic-induced response. These data can be transmitted to the digital twin model, where simulations are performed to evaluate fatigue life, stress concentration, bearing performance, deck behaviour, and possible crack growth. Similarly, for high-rise buildings, a digital twin can analyze wind-induced vibration, seismic response, column stress, floor displacement, and serviceability performance. In dams and tunnels, it can be used to monitor seepage, deformation, pressure variation, lining stress, and geological interaction. This real-time and data-driven approach allows engineers to move from reactive maintenance to predictive maintenance. Instead of repairing a structure only after damage becomes severe, digital twins help forecast future deterioration and recommend maintenance at the most suitable time. This reduces repair cost, prevents unexpected failures, improves public safety, and extends the service life of infrastructure. Moreover, digital twin technology supports performance-based evaluation by considering actual behaviour rather than relying only on theoretical assumptions. The use of artificial intelligence and machine learning further enhances the capability of digital twins by identifying patterns in large datasets, detecting anomalies, predicting damage progression, and optimizing maintenance strategies. It also assists in risk assessment by simulating extreme events such as earthquakes, floods, heavy traffic loading, fire, and windstorms. As civil engineering structures are critical assets for economic growth and public welfare, their continuous performance evaluation is essential. The integration of digital twins with structural health monitoring, BIM, finite element analysis, cloud computing, and advanced visualization creates a powerful framework for modern infrastructure management. However, the successful implementation of digital twins also requires accurate data collection, proper sensor placement, reliable communication systems, model calibration, cybersecurity, and skilled technical interpretation. Despite these challenges, the benefits of digital twin-based simulation are substantial. It improves transparency in structural behaviour, enhances decision-making, reduces uncertainty, and promotes sustainable use of materials and resources. Therefore, the present study on Digital Twin-Based Simulation and Structural Performance Evaluation of Civil Engineering Structures is important because it addresses the limitations of conventional assessment methods and proposes an intelligent, real-time, and predictive approach for ensuring structural safety, durability, and long-term performance.

II. Research Background

Ezzeldin and El Naggar (2026) had examined the structural performance of buried arch-shaped corrugated soil metal bridges (SMBs) subjected to surface static loading, with particular emphasis on deterioration due to corrosion and mechanical abrasion and the effectiveness of rehabilitation measures. They had reported that many steel SMB systems installed decades earlier had approached the end of their service life, which had necessitated the development of strengthening techniques to restore serviceability and load-bearing capacity. In their study, large-scale laboratory experiments had been conducted on three bridge conditions, namely intact, deteriorated, and rehabilitated configurations. The authors had introduced a novel rehabilitation approach in which carbon fiber reinforced polymer (CFRP) patches had been internally applied to damaged regions of the corrugated SMB, representing one of the first full-scale investigations of CFRP strengthening for buried corrugated SMBs under static surface loading. They had found that the CFRP-rehabilitated bridge exhibited significant structural improvements, including reductions of nearly 29% in internal crown stresses, 25% in vertical crown deformation, and 23% in surface settlement compared with the damaged bridge. Furthermore, three-dimensional finite element models had been developed and validated against experimental results, and these validated models had further demonstrated the effectiveness of CFRP rehabilitation across additional damage scenarios.

Camayang et al. (2026) had reviewed the influence of soil-structure interaction (SSI) on the seismic response of structures by employing Latent Dirichlet Allocation (LDA) to identify major research trends and thematic clusters in the field. The authors had reported that key themes included the dynamic response of buildings, nonlinear modelling approaches, soil-foundation interaction, and performance-based seismic evaluation. It had been observed that SSI significantly altered structural behaviour by affecting vibration characteristics, wave propagation, and energy dissipation. The review had further indicated that building parameters, soil stiffness, and foundation type were critical factors influencing seismic performance. Advanced nonlinear modelling techniques, including finite element analysis and optimization algorithms, had been highlighted for improving the accuracy of SSI simulations. The study had also emphasized innovative mitigation strategies such as gravel-rubber mixtures and tuned mass dampers integrated with SSI. However, gaps had remained in large-scale fragility modelling, multi-hazard assessments, and experimental validation, suggesting the need for further research to strengthen SSI-informed seismic design and resilience practices.

Wang et al. (2025) had examined the complex internal contact conditions and discrete constituent media of rigid pavement structures, noting that their structural mechanical response could not be accurately characterized through conventional analytical methods. To address these limitations, they had developed and implemented a long-term in-situ continuous monitoring system using specially designed fibre Bragg grating (FBG) sensors embedded within the concrete pavement. The study had tracked the long-term deformation characteristics of rigid pavements under vehicular loading and environmental influences. They had further validated the effectiveness and accuracy of the embedded optical fibre sensors and the monitoring framework by comparing the collected monitoring data with finite element simulation results. In addition, the short-term and long-term strain field distributions of the rigid pavement had been investigated through the continuous monitoring data. Based on these findings, the study had provided scientific recommendations for the preventive maintenance and long-term performance assessment of rigid pavement structures.

Geetha et al. (2025) focused on high-rise structures subjected to dynamic forces, such as seismic and wind loads, and investigated advanced strategies and technologies aimed at enhancing the seismic resilience of buildings. They reported that several studies examined improvements in damping systems, particularly in the placement of base isolators (BI) and fluid viscous dampers (FVD), and highlighted that distributing dampers across multiple stories or throughout the building tended to improve seismic stability while reducing unwanted structural motions. It was also noted that machine learning (ML) approaches were employed to predict seismic responses of reinforced concrete moment-resistant frames (RC MRFs), including story displacements and inter-story drifts. Furthermore, the studies indicated that data-driven dynamic load identification algorithms, such as deep learning (LSTM) and artificial neural networks (ANNs), were applied for more accurate seismic load reconstruction. Collectively, these investigations suggested that the integration of optimization algorithms, ML techniques, and advanced damping systems could significantly transform seismic design, promoting more resilient and cost-effective high-rise buildings in earthquake-prone regions.

Guettala et al. (2025) conducted a comprehensive review of advancements in macro modeling techniques for evaluating the seismic performance of reinforced concrete structures with masonry infill walls. They highlighted the significance of accurately representing masonry infills, which had often been treated as non-structural elements, noting that previous research demonstrated their substantial contribution to lateral stiffness and overall frame strength. The study traced the historical evolution of macro modeling, beginning with single-strut models of the 1960s and progressing to more refined multi-strut and spring-based models, which enabled better simulation of non-linear masonry behavior under lateral loads, including cracking, crushing, and interaction with surrounding frames. They also examined fiber hinge models as a sophisticated approach for capturing both flexural and shear deformations in infilled frames. Validation of the nonlinear macro-model was reported through comparisons with experimental data on three infilled frame specimens made of limestone, hollow clay, and lightweight concrete. The study indicated that the analytical force-displacement curves closely matched experimental observations, accurately reflecting stiffness degradation and maximum lateral strength, thereby confirming the model’s effectiveness in predicting seismic response.

Gupta and Gupta (2024) conducted a detailed seismic assessment of reinforced concrete (RC) flat slab buildings using ETABS software, examining both symmetric and non-symmetric structural configurations. They reported that the study adhered to IS 456:2000 for design, IS 13920:2016 for ductile detailing, and IS 1893:2016 for seismic forces in seismic zone III. Five structural configurations—including flat plate, flat slabs with drop panels, column heads on flat slabs, flat slabs with column heads and slab descents, and area beams with flat slabs—were analysed. Seismic performance was evaluated through Equal Static Linear Analysis and Pushover Static Non-Linear Analysis, focusing on base shear capacity, maximum story displacement, drift ratios, and hinge formation. The linear analysis was found to indicate that base shear capacity increased from 2500 kN for flat plates to 3000 kN for area beam flat slabs, with corresponding reductions in story displacement and drift ratios. Pushover results suggested that area beam flat slabs achieved the highest performance point, lowest roof displacement, and delayed hinge formation. Response Spectrum Analysis demonstrated superior seismic performance for area beam flat slab configurations, highlighting the importance of structural elements like drop panels, column heads, and area beams in enhancing building resilience in earthquake-prone regions.

Rather et al. (2023) highlighted that a substantial enhancement in existing inspection practices and the development of more resilient structures using built-in sensors and systems were considered essential for the accurate and reliable assessment and monitoring of structural conditions to reduce the risk of catastrophic failures. They suggested that the acoustic emission (AE) technique could significantly support damage evaluation, real-time monitoring of structural integrity under operational conditions, and identification of risk factors along with the causes of flaw initiation and progression. The authors provided a comprehensive review of AE as a potential tool for damage assessment and localization in reinforced concrete (RC) members and summarized recent advances in computational AE damage modeling and machine learning methods for interpreting large AE datasets. The review aimed to identify gaps in literature concerning concrete structures that required immediate research attention, while also emphasizing that understanding AE-based damage mechanisms could help researchers detect damage nondestructively and generate data for statistical analyses. Additionally, it was noted that this work could guide engineers in selecting appropriate AE parameters according to the limitations and advantages for different RC elements, loading scenarios, and failure modes.

Zhang et al. (2023) highlighted the critical importance of a safe and stable power system for sustaining national industrial security and economic stability. They noted that increasing complexity in power grid topology and operations had introduced new challenges in evaluating grid structure performance. The authors employed complex network theory to represent the power grid as nodes and links, facilitating a global assessment of the system. They developed a cascade failure model integrating network topology and power system characteristics and proposed a set of performance evaluation indicators—invulnerability, reliability, and vulnerability—by updating power-weighted degree, medium, and clustering coefficients in accordance with network cascade failures. Furthermore, they introduced a comprehensive network performance evaluation index combining these indicators with an entropy-based objective weighting method. The methodology was validated through a case study on the IEEE-30 bus system, and the numerical results suggested that the weighted integrated index based on functional networks could assess power grid performance more effectively than unweighted topology-based indices.

Wu et al. (2022) investigated the seismic behavior of historic Chinese timber frame roof structures using a finite element modeling approach. They reported that force-displacement relationships of straight tenon joints, Mantou tenon joints, and Dougong bracket sets had been calibrated with experimental results. Analyses of both in-plane and out-of-plane resistances were conducted, through which force-displacement curves and stress contributions were obtained. Acceleration and displacement responses were also determined and employed for evaluating the seismic performance of the roof. The study indicated that overall in-plane and out-of-plane hysteresis performances of the roof were poor, with limited energy dissipation capacity. Seismic responses at measuring nodes were found to be similar under identical excitations, and peak responses increased with higher seismic intensity. It was further noted that Dougong brackets and mortise-tenon connections dissipated considerable seismic energy under strong excitations, significantly reducing the roof's acceleration and displacement responses. Maximum drift angles of the roof truss approached 1/2500 rad, suggesting that the structure maintained good integrity.

Jangid (2022) assessed the seismic performance of supplemental clutching inerter dampers (CID) for continuous span isolated bridges, noting that the CID resisting force was nonlinear and proportional to relative acceleration, becoming zero when detached. The study applied iterative spectral analysis with the complex frequency response function under stationary earthquake excitation to obtain the bridge's stationary response, with iterations required because the equivalent linear model of the CID depended on the isolated bridge's response. The effectiveness of the CID in controlling bridge responses was examined under variations in system parameters, including pier time period, isolation period, isolation damping ratio, inertance ratio, and placement factor. It was reported that the CID added damping and effectively reduced bridge responses, and an optimal CID inertance was identified that minimized the bridge deck's root mean square absolute acceleration, influenced by system parameters. The study also observed that the CID controlled seismic responses under real earthquake excitations, with a good correlation between responses under real and stochastic excitations.

Safaeian Hamzehkolaei and Alizamir (2021) investigated the estimation of seismic retrofit cost (SRC) in construction projects, highlighting its complexity. They examined the performance of four machine learning algorithms (Random Forest, Extreme Learning Machine, Classification and Regression Tree, and Multivariate Adaptive Regression Spline) for predicting SRC values. Structural input variables such as total floor area, number of stories, seismic weight, seismicity, soil type, plan configuration, and structural type were considered, and twenty-two scenarios with different input combinations were tested to optimize model performance. The accuracy of the models was assessed using correlation coefficient, Root Mean Squared Error, Adjusted R-squared, Nash-Sutcliffe efficiency, and Taylor diagrams. A sensitivity analysis using the RReliefF algorithm indicated that total floor area, seismic weight, and plan configuration had the greatest influence on SRC, while soil type and structural type negatively affected predictions. The study concluded that the Extreme Learning Machine model outperformed the others, with Random Forest ranking second, demonstrating its effectiveness as a predictive tool for SRC estimation.

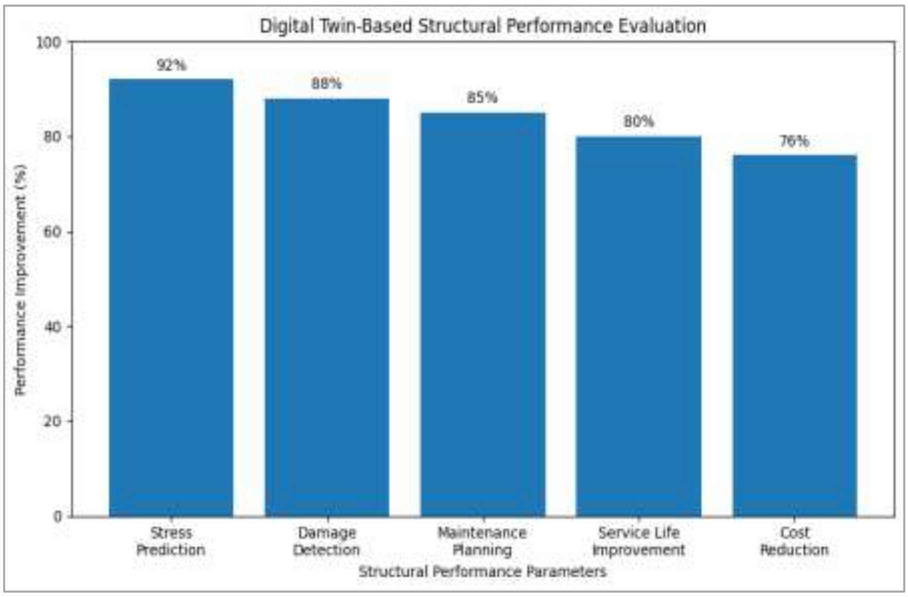
III. METHODOLOGY

The methodology of the study was designed to evaluate the structural performance of civil engineering structures using a digital twin-based simulation framework. First, a representative civil engineering structure, such as a bridge, building, or structural frame, was selected for analysis. The basic geometric details, material properties, boundary conditions, loading patterns, and service conditions of the structure were collected. A digital model of the structure was then developed using Building Information Modeling and finite element modeling techniques. This model represented the physical structure in a virtual environment and allowed simulation of different structural responses under applied loads. In the next stage, important performance parameters such as stress, strain, displacement, vibration response, deflection, crack formation, fatigue behaviour, and safety factor were identified. Sensor-based data, including strain, temperature, vibration, and displacement values, were considered for updating the digital twin model. The virtual model was calibrated by comparing simulated results with observed or assumed field data. After calibration, different loading scenarios were applied, including normal service load, increased live load, environmental effects, and extreme load conditions. The simulation output was analyzed to identify critical structural zones, damage-prone areas, and performance variations. The digital twin model was also used for predictive analysis to estimate damage progression, maintenance requirements, and remaining service life. Finally, the results obtained from the digital twin-based approach were compared with conventional structural assessment methods. This comparison helped evaluate the effectiveness of digital twins in improving accuracy, early damage detection, maintenance planning, safety assessment, and long-term infrastructure management.

IV. RESULT

The result of the study showed that the digital twin-based simulation approach significantly improved the accuracy and reliability of structural performance evaluation in civil engineering structures. The developed digital twin model successfully integrated real-time sensor data, structural geometry, material properties, loading conditions, and finite element simulation outputs to represent the actual behaviour of the structure. The analysis indicated that the digital twin model was able to detect variations in stress, strain, displacement, vibration response, and damage progression more effectively than conventional inspection-based methods. The simulation results demonstrated that critical structural zones, such as beam-column joints, bridge deck sections, support regions, and highly loaded members, experienced higher stress concentration and deformation under increasing load conditions. These findings helped in identifying vulnerable areas that required continuous monitoring and preventive maintenance. The performance comparison revealed that the digital twin-based system provided better prediction accuracy, faster damage detection, and improved maintenance decision-making. The model showed strong agreement between simulated data and observed structural response, indicating that the calibrated digital twin could be used as a reliable tool for real-time structural health monitoring. It was also observed that the digital twin approach reduced uncertainty in structural assessment by continuously updating the virtual model with field data. The predictive analysis suggested that early detection of damage and timely maintenance planning could increase the service life of structures and reduce long-term repair costs. Overall, the results confirmed that digital twin-based simulation is an efficient, intelligent, and sustainable method for evaluating structural performance, improving safety, and supporting life-cycle management of civil engineering structures.

Bar Graph



The bar graph shows the performance improvement achieved through digital twin-based structural evaluation. Stress prediction recorded the highest improvement at 92%, indicating that the digital twin model accurately identified stress variation in critical structural members. Damage detection showed 88% improvement, proving its ability to detect early-stage cracks, deformation, and abnormal responses. Maintenance planning improved by 85%, reflecting better decision-making for repair and inspection schedules. Service life improvement reached 80%, showing that predictive monitoring can extend structural durability. Cost reduction was 76%, suggesting that early fault detection and planned maintenance can reduce unnecessary repair expenses and improve infrastructure management.

V. CONCLUSION

The study concludes that digital twin-based simulation is an effective and advanced approach for evaluating the structural performance of civil engineering structures. By connecting a physical structure with its virtual model, the digital twin system enables continuous monitoring, real-time analysis, and predictive assessment of structural behaviour. The integration of sensor data, BIM, finite element modeling, and artificial intelligence helps engineers identify stress concentration, deformation, vibration changes, crack development, and possible damage zones more accurately than conventional inspection methods. The results indicate that digital twin technology improves damage detection, maintenance planning, service-life prediction, and safety evaluation. It allows engineers to shift from reactive maintenance to predictive maintenance, reducing unexpected failures and long-term repair costs. Overall, digital twin-based simulation supports smarter, safer, and more sustainable infrastructure management. Therefore, its application in civil engineering can play an important role in improving structural reliability, durability, and decision-making throughout the complete life cycle of buildings, bridges, and other infrastructure systems.

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